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LEPTOGENESIS IN MINIMAL SUPERSYMMTRY STANDARD MODEL

NG. K. FRANCIS

Department of Physics, Tezpur University, Tezpur, Assam, India

ABSTRACT

We study leptogenesis in the minimal supersymmetric standard model and compare with the non-supersymmetric Fukugita-Yanagida scenario. We identify that the picture of leptogenesis is qualitatively quite different from the non-supersymmetric case, but it turns out that, quantitatively, they are very similar. The lepton number asymmetries in fermions and scalars do not equilibrate, and are related vis a non-vanishing gaugino chemical potential. The recent great discovery of this century, the detection of Higgs bosons mass of 126 Ge V and reactor neutrino mixing angle non-zeroθ_{13}make all the more plausible for leptogenesis. Over-production of gravitinos in SUSY or MSSM is a big hindrance in leptogenesis. Besides inflation models, there are three well-known approaches, “soft leptogenesis”, “resonant leptogenesis” and “non-thermal leptogenesis” to overcome gravitinos problem. We investigate the last one.We also discuss the different results present in the literature and compare with our results. Inflaton mass needed to produce the observe baryon asymmetry 6.5×10^{-10} GeV is found to be 5.60×10^{12} GeV corresponding to the reheating temperature 8.87×10^{6} GeV.

KEYWORDS: Leptogenesis, MSSM, Inflaton Mass

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1. INTRODUCTION

The discovery of tiny but very small non-zero neutrino mass [1] has promoted leptogenesis to an utmost attractive scenario to explain the origin of the matter-antimatter asymmetry in the Universe. A very interesting scenario in non-supersymmetric version originally proposed by Fukugita and Yanagida [2], for the generation of cosmological baryon asymmetry of the Universe (BAU), is based on the production of an initial lepton asymmetry by the out-of-equilibrium decays of heavy (m>>TeV) electroweak singlet Majorana neutrinos. The lepton asymmetry is then partially converted to a baryon asymmetry through an anomalous sphaleron weak interaction [3]. The possibility of explaining two apparently unrelated experimental facts (neutrino oscillations and the baryon asymmetry) within a single framework has boosted the interest in leptogenesis studies, leading to important development in the field, as for example the inclusion of thermal corrections [4], spectator processes [5,6], flavor effects[7-11], CP asymmetry in scattering [12],lepton asymmetry from the decays of the heavy right-handed Majorana neutrinos [13,14], non-thermal decay of inflaton to Majorana neutrinos [15] and many more.The recent great discovery of this century, the detection of Higgs mass of 126GeV [16] and reactor neutrino mixing angle non-zeroθ_{13}[17] make all the more plausible for leptogenesis.

We opine that in spite of all these advancements, a detail and a proper treatment of leptogenesis in the supersymmetric (SUSY) scenario is yet to be done. And despite its current experimental elusiveness, SUSY leptogenesis remains theoretically well motivated and appealing generalization of leptogenesis for the following reasons: while the standard model (SM) equipped with the seesaw mechanism provides the simplest way to realize leptogenesis, such a

framework is plagued by an unpleasant fine-tuning problem. For a hierarchical heavy right-handed (RH) Maojorana neutrino, successful leptogenesis requires generically a scale for the singlet neutrino masses that is much larger than the electroweak scale [18] but at the quantum level the gap between these two scales becomes unstable. Low-energy SUSY can naturally stabilize the required hierarchy, and this provides a healthy motivation for studying leptogenesis in the framework of the supersymmetrized version of the seesaw formula. Leptogenesis from SUSY has been studied in many places, both in dedicated works [19] or in conjunction with SM leptogenesis [cf. 4]. However, there are two basic requirements whatsoever for SUSY studies. First, the supersymmetry breaking scale should not exceed by much the 1 TeV scale, is that above a temperature $T \sim 5 \times 10^7$ GeV the particle and superparticleleptonic density asymmetry do not equilibrate. A second feature is that when soft supersymmetry breaking parameters are neglected, additional anomalous global symmetries that involve SU (2) and SU (3) fermion representations join [20]. Finally, the inclusion of the SUSY superpartners at above the electroweak is essential for the strong phenomenological motivation for SUSY, which is to explain the stability of the electroweak scale under radiative corrections, and maintenance of the hierarchy between the electroweak scale and the GUT or Planck scales.

It is well understood, that the minimal supersymmetric standard model (MSSM) contains only a few of the possible gauge invariant couplings. In this article, we wish to investigate the BAU in MSSM. However, it may be pointed out that, the origin of lepton asymmetry for non-SUSY [cf. 2], SUSY[21], and also due to decay of heavy scalar neutrinos produced non-thermally by the coherent oscillations of the scalar field at the end of inflation has been discussed by Murayama et.al. [22] are the same. A key ingredient for all these scenarios is the one-loop violating asymmetry involved in the heavy (s)neutrino decay, see Figure 1 and the consideration of this quantity will be the main trust of this work. For comparison of these two scenarios interested reader can see our earlier work on leptogenesis in non-supersymmetric standard model [23].

The detailed plan of the paper is as follows. In Section 2, we presentminimal supersymmetric standard model (MSSM). Section 3 discusses the gravitino-over-production problem.The numerical and analytic results for different neutrino mass models are given in Sections 4. We conclude with Section 5.

2. MINIMAL SUPERSYMMETRIC STANDARD MODEL (MSSM)

In the Minimal Supersymmetric Standard Model (MSSM) complemented with three RH neutrinos N_i(i=1,2,3) and the corresponding superpartners $\widetilde{N}_i$, the picture of leptogenesis is qualitatively quite different from the non-supersymmetric case, but it turns out that, quantitatively, they are very similar. The interactions of the heavy (s) neutrino field can be derived from the leptonic superpotential [24]

$$W = \frac{1}{2} M_i N_i N_i + \lambda_{ij} L_i H_u N_j + f_i^{'} L_i H_d E_i, \tag{1}$$

Where $L_i$and $E_i$are the SU(2) lepton doublets and singlets chiral superfields, respectively, and $H_u$andH_d are the Higgs chiral superfields. The scalar components of both Higgs bosons, which we denote $\Phi_{u,d}$, have vacuum expectation values: $< \Phi_u > \equiv v_u = v\ sin\beta$and $< \Phi_d > \equiv v_d = v\ cos\beta$where $v = 174$GeV. Their ratio is then given by

$$tan\beta = \frac{v_u}{v_d}, \tag{2}$$

When flavor effects are included in supersymmetric leptogenesis, the value of $tan\beta$is relevant because $f_i^{'2} = (1 + tan^2\beta)f_i^2$where$f_i$ is the SM Yukawa coupling. Typically, supersymmetry breaking terms are of no relevance for

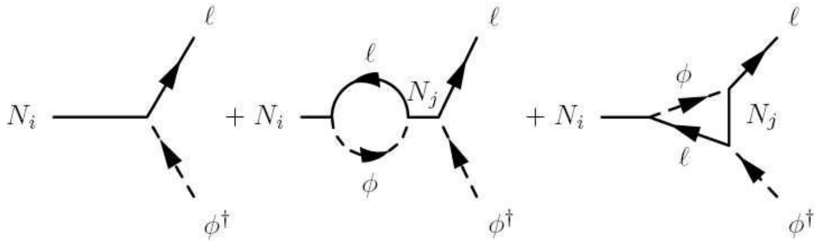

Figure 1: The Diagrams Necessary to Compute the CP Asymmetry in Leptogenesis Due to Decay of RH Neutrino at Tree Level (1st Figure) and One Loop, Given by the Vertex Correction (2rd Figure) and the Self-Energy Correction (3rd Figure)

the mechanism of lepton number generation, and we are left with the following trilinear couplings in the Lagrangian, written in terms of four-component spinors,

$$-\lambda_{ij}\left[M_i\tilde{L}_i^\dagger\tilde{N}_i\Phi_u + \bar{\mathrm{l}}_\mathrm{i}\,\mathrm{P_R}\mathrm{N_i}\Phi_u + \bar{\mathrm{l}}_\mathrm{i}\,\mathrm{P_R}\tilde{\phi}^c\tilde{N}_i + \tilde{L}_i^\dagger\mathrm{P_R}\tilde{\phi}^c N_i\right] + h.c., \tag{3}$$

Where$\tilde{L}$, $\tilde{\phi}$ and $\tilde{N}$ denote sleptons, higgsnos and singlet sneutrinos, respectively.

From these couplings one obtains the tree-level relations

$$\Gamma_{N_i,l} + \Gamma_{N_i,\tilde{l}} = \Gamma_{N_i,\tilde{L}} + \Gamma_{N_i,\tilde{l}^\dagger} = \Gamma_{\tilde{N}_i^\dagger l} = \Gamma_{\tilde{N}_i,\tilde{L}} = \frac{(h^\dagger h)_{ii}}{8\pi}M_{i.} \tag{4}$$

We will denote the corresponding asymmetry parameters in the supersymmetric case with a tilde. There are now new diagrams contributing to the CP asymmetry. On top of the usual contributions shown in Figure 1, there are three additional sources coming from the decay of the heavy neutrinos into sleptons, from the decay of RH sneutrinos into leptons and from the decay of RH sneutrinos into sleptons. One can then define a CP asymmetry for the decay of RH neutrinos into leptons and sleptons, and another one for the decay of RH sneutrinos into leptons and sleptons, as follows:

$$\tilde{\epsilon}_N \equiv -\frac{(\Gamma_{N\tilde{L}}+\Gamma_{NL})-(\Gamma_{N\tilde{L}^\dagger}+\Gamma_{N\bar{l}})}{\Gamma_N}, \tag{5}$$

$$\tilde{\epsilon}_{\tilde{N}} \equiv -\frac{(\Gamma_{\tilde{N}^\dagger l}+\Gamma_{\tilde{N}\tilde{L}})-(\Gamma_{N\tilde{L}^\dagger}+\Gamma_{N\bar{l}})}{\Gamma_N} \tag{6}$$

Where Γ_N and$\Gamma_{\tilde{N}}$denote the total decay rate of RH neutrinos and RHsneutrinos, respectively.

These CP asymmetries were computed in [25] to be

$$\tilde{\epsilon}_N \equiv \tilde{\epsilon}_{\tilde{N}} = \frac{1}{8\pi}\frac{1}{(h^\dagger h)_{ii}}\sum_{j=2,3}\mathrm{Im}[(h^\dagger h)_{ij}]^2[\mathrm{f}\,(\frac{M_j^2}{M_i^2})\ \mathrm{g}(\frac{M_j^2}{M_i^2})] \tag{7}$$

Where f(x) and g(x) represent the contributions from vertex and self-energy corrections respectively and given by$f(x) = \sqrt{x}\ln\left(1 + \frac{1}{\mathrm{x}}\right)$ and$g(x) = \frac{2\sqrt{x}}{x-1}$. For x>>1,

$$f(x) + g(x) \approx \frac{3}{\sqrt{x}} \tag{8}$$

In the hierarchical limit (x>>1), the CP asymmetry in the MSSM is therefore twice as large as the one in the SM. Consequently, the factor $3/8$ will appear for MSSM in place of $3/16$ in the expression of CP asymmetry since there are two Higgses in MSSM [26].

$$\tilde{\epsilon}_N \equiv \tilde{\epsilon}_{\tilde{N}} = \frac{3}{8\pi}\left[\frac{\mathrm{Im}[(\mathrm{h}^{\dagger}\mathrm{h})_{12}^{2}]}{(\mathrm{h}^{\dagger}\mathrm{h})_{11}}\frac{\mathrm{M}_1}{\mathrm{M}_2} + \frac{\mathrm{Im}[(\mathrm{h}^{\dagger}\mathrm{h})_{13}^{2}]}{(\mathrm{h}^{\dagger}\mathrm{h})_{11}}\frac{\mathrm{M}_1}{\mathrm{M}_3}\right] \tag{9}$$

Finally one obtains for the baryon-to-photon ratio

$$\eta_B \simeq 1.03 \times 10^{02}\tilde{\epsilon}_N \kappa_1^f \tag{10}$$

As we have seen, there are new decay channels in the MSSM, which yield an enhancement of the CP asymmetry by a factor 2. On the other hand, there is also an enhancement of the washout by a factor of 2, which implies that the constraints on M_1, T_R andm_1 derived in earlier on SM leptogenesis remain almost essentially unchanged [27].

3. THE GRAVITINO-OVER-PRODUCTION PROBLEM

The gravitino is the supersymmetric partner of the graviton in a supergravity theory and its over-production in SUSY or MSSM is a big hindrance in leptogenesis [28]. Assuming a period of inflation and reheating before leptogenesis occurs, the lower bound on the initial temperature of leptogenesis T_{in} can be identified with a lower bound on the reheat temperature T_R of the Universe after inflation. And gravitinos put a severe constraint on the bound of the reheating temperature T_R. In the post-inflation era, these gravitino are produced in a thermal bath due to annihilation or scattering processes of different standard particles. The relic abundance of gravitino is proportional to the reheating temperature of the thermal bath. Besides this the exact scale of the gravitino mass and its main decaying channel vary in different scenarios. There are also several schemes of how supersymmetry is broken and how the universe inflates.

It is well known that within locally supersymmetric theories, gravitinos are produced during the reheating phase. The point is actually that they may be overproduced, i.e. their abundance may overclose the Universe, leading to the so-called *gravitino problem* (for details see[29-33]).There are two situations to be distinguished: unstable ones and stable gravitinos.

In gravity mediated SUSY breaking models, gravitinos are unstable particles with mass $m_{3/2} \sim \mathcal{O}(100\ \text{GeV} - 10\ \text{TeV})$ [34]. In this scenario, it may lead to large entropy production when they decay during or after big-bang nucleosynthesis (t_{BBN}~$100\ \text{sec}$), spoiling the nice agreement between theory and observations. And lifetime [35] is given by

$$\tau_{3/2} \simeq 4 \times 10^5 \left(\frac{m_{3/2}}{1\ \text{TeV}}\right)\ sec, \tag{11}$$

Unless the gravitino is relatively heavy: $m_{3/2} \sim 10\ \text{TeV}$. The decay of gravitino (Gravitinos majorly decay into photons and photinos ($\tilde{g} \rightarrow \tilde{\gamma}\gamma$)or neutrinos andsneutrinos ($\tilde{g} \rightarrow \tilde{\nu}\nu$)would dilute the abundance of light element $(D,\ {}^3He,\ {}^4He,\ {}^7Li\ \ldots)$ produced in Nucleosynthesis. In Ref. (36), the bounds on reheating temperatureis given by

$$T_R < 10^7\text{GeV} \tag{12}$$

In such case the baryon-to-photon ration given by BBN [37] is

$$\eta_B \simeq (5.5 \pm 1.0) \times 10^{-10}. \quad (13)$$

If gravitinos are stable, e.g. in the gauge mediated SUSY breaking model, we have

$m_{3/2} < O(10)$GeV.In this scenario gravitino is the lightest supersymmetric particle (LSP), and therefore represents a good candidate of dark matter (DM) particle [38-42]. The bound on the reheating temperature comes from the density of the gravitino. In order for gravitinosnot to exceed the dark matter abundance, the reheat temperature has to

$$T_R \lesssim 10^7 - 10^9\text{GeV} \quad (14)$$

And latest and better result by WMAP [43]

$$\eta_B \simeq (6.5^{+0.4}_{-0.3}) \times 10^{-10}. \quad (15)$$

But, thermal leptogenesis in SUSY SO (10) with high see-saw scale easily satisfies the lower bound. Consequently, whatever specific scenario of supergravity one considers, there is a clear tension with the lower bound from leptogenesis say given by Davidson-Ibarra bound$T_R \geq (10^8 - 10^{10})$ GeV [44], so canonical Leptogenesis must be modified insome way. Different ways to relax this tension have been proposed in the literature. Let us give three well-known examples.

Apart from inflation models [45], the first possibility is provided by “soft leptogenesis” [46, 47], which is a supersymmetric scenario which requires only one heavy RH neutrino. The interference between the CP-odd and CP-even states of the heavy scalar neutrino resembles very much the neutral kaon system. The mass splitting as well as the required CP violation in the heavy sneutrino system comes from the soft supersymmetry breaking A and B terms, associated with the Yukawa coupling and mass term ofN_1, respectively. The lower bound on thereheat temperature in this scenario can go as low as 10^6GeV [cf. 27].

It is also possible to use the enhancement of the CP asymmetry for quasi-degenerate heavy neutrinos

Table 1: MSSM Results: Heavy Right Handed Majorana Neutrino Masses M_j for QDN with Normal and Inverted Ordering Mode for $tan^2\,\theta_{12}$ = 0.45. The Entry (m, n) Indicates for Charged Mass Matrix (6, 2) or up Quark Mass Matrix (8.4) of Dirac Neutrino Mass Matrix m_{LR}, as Explained in the Text [cf. 23]

TYPE	(m, n)	M_1(GeV)	M_2(GeV)	M_2(GeV)
NH-IA	(6,2)	$3.8659\text{x}10^9$	$-5.523\text{x}10^{12}$	$9.8256\text{x}10^{14}$
	(8,4)	$4.6414\text{x}10^7$	$-7.41740\text{x}10^{11}$	$9.0097\text{x}10^{13}$
NH-IB	(6,2)	$3.647\text{x}10^9$	$8.3219\text{x}10^{12}$	$8.7528\text{x}10^{14}$
	(8,4)	$6.699\text{x}10^7$	$8.1238\text{x}10^{10}$	$9.2527\text{x}10^{14}$
IH-IA	(6,2)	$2.858\text{x}10^8$	$-9.87708\text{x}10^{12}$	$6.373\text{x}10^{14}$
	(8,4)	$3.6910\text{x}10^7$	$-1.3275\text{x}10^{11}$	$6.89\text{x}10^{14}$
IH-IB	(6,2)	$1.5153\text{x}10^9$	$6.8234\text{x}10^{12}$	$7.5098\text{x}10^{14}$
	(8,4)	$7.393\text{x}10^7$	$9.4809\text{x}10^{11}$	$8.8091\text{x}10^{14}$

$M_1 \simeq M_2 \simeq M_3$ [cf. 25] inorder to relax the lower bound on the reheat temperature. This inspired the scenario of “resonant leptogenesis” [48-52], where at least two of the three RH neutrinos are mass degenerate. The lepton asymmetry ϵ_1 can be enhanced drastically even in the small mass case $M_1 \backsim M_2 \backsim 10^7$GeV. However, one has to impose a mechanism to explain why the RH neutrino masses are degenerate.

The third possibility is to produce RH neutrinos non-thermally in the decays of the inflaton [53-57]. F. Hah-Woernle and M. Pliimacherin Ref. [58] showed that the lower bound on T_R from non-thermal leptogenesis can be

relaxed in this way by two orders of magnitude than in the thermal leptogenesis. This possibility is the main objective of this paper. In this work, we do not investigate “resonant leptogenesis” and “soft leptogenesis” but reserve for future work.

4. NUMERICAL ANALYSIS AND RESULTS

In our earlier work we have investigated for the leptogenesis in non-supersymmetric Standard Model case. Here we simply show the results based on MSSM leptogenesis without giving detail explanations. The ideas of calculations are the same as SM case. So, for details formalism of leptogenesis and analysis we refer the interested reader to Ref. [cf. 23]. In case of MSSM, there is no major numerical change with respect to the non-supersymmetric case in the estimation of baryon asymmetry. One expects approximate enhancement factor of about $\sqrt{2}(2\sqrt{2})$ for strong (weak) washout regime.

Table 2: MSSM Results: Yukawa Coupling Matrix Multiplication First Term $(h^{\dagger}.h)_{11}$, Effective Mass $(\widetilde{m}_1(eV)$, Efficiency/Dilution Factor (k_1), Lepton Asymmetry (ϵ_1) and Baryon Asymmetry (η_B) for Neutrino Mass Models with $tan^2\theta_{12}$ = 0.45

TYPE	(m,n)	$(h^{\dagger}.h)_{11}$	$\widetilde{m}_1(eV)$	k_1	ϵ_1	η_B
NH-IA	(6,2)	$2.62\text{x}10^{-4}$	2.25287	$6.62\text{x}10^{-6}$	$3.64\text{x}10^{-7}$	$2.25\text{x}10^{-14}$
	(8,4)	$5.49\text{x}10^{-8}$	0.49905	$2.19\text{x}10^{-3}$	$2.53\text{x}10^{-9}$	$5.42\text{x}10^{-15}$
NH-IB	(6,2)	$2.50\text{x}10^{-6}$	0.13941	$8.99\text{x}10^{-3}$	$1.92\text{xl}0^{-8}$	$2.13\text{x}10^{-12}$
	(8,4)	$4.32\text{x}10^{-9}$	0.08731	$1.53\text{x}10^{-3}$	$2.32\text{xl}0^{-12}$	$1.77\text{x}10^{-16}$
IH-IA	(6,2)	$5.31\text{x}10^{-4}$	15.354	$4.45\text{x}10^{-5}$	$6.95\text{x}10^{-8}$	$3.24\text{x}10^{-14}$
	(8,4)	$3.35\text{x}10^{-7}$	0.27512	$4.22\text{x}10^{-3}$	$4.65\text{x}10^{-9}$	$1.09\text{x}10^{-13}$
IH-IB	(6,2)	$3.45\text{x}10^{-7}$	0.16653	$7.37\text{x}10^{-4}$	$1.29\text{xl}0^{-8}$	$7.30\text{x}10^{-13}$
	(8,4)	$8.33\text{x}10^{-9}$	0.09423	$1.08\text{x}10^{-3}$	$1.59\text{x}10^{-12}$	$2.18\text{x}10^{-16}$

Non-Thermal Leptogenesis via Inflaton (ϕ) Decay

In non-thermal leptogenesis [cf. 53-57] the right-handed neutrinos $N_i, (i = 1, 2, 3$ with masses $M_1, M_2, M_3)$ produced through the direct non-thermal decay of the inflaton ϕ interact only with leptons and Higgs through Yukawa couplings. In supersymmetric models the superpotential that describes their interactions with leptons and Higgs is [59]

$$W_1 = Y_{ia} N_i L_a H_U \tag{16}$$

Where Y_{ia} is the matrix for the Yukawa couplings, $H_U$is the superfield of theHiggs doublet that couples to up-type quarks and L_a $(a = e, \mu, \tau))$ is the superfield of the lepton doublets.Furthermore, for supersymmetric models the interaction between inflaton and right-handed neutrinos is described by the superpotential [60]

$$W_2 = \sum_{i=1}^{3} \lambda_i S N_i^c N_i^c \tag{17}$$

Where λ_i are the Yukawa couplings for this type of interaction and $S$is a gauge singlet chiral superfield for the inflaton. With such a superpotential the inflaton decay rate Γ_ϕ is given by [60]

$$\Gamma_\phi = \Gamma(\phi \rightarrow \mathrm{N_i N_i}) \approx \frac{|\lambda_i|^2}{4\pi} \mathrm{M_\phi} \tag{18}$$

Where M_Φ is the mass ofinflaton ϕ. The reheating temperature (T_R) after inflation is given by [61],

$$T_R = \left(\frac{45}{4\pi^3 g_*}\right)^{1/4} (\Gamma_\phi M_p)^{1/2} \tag{19}$$

Table 3: Theoretical Bound on Reheating Temperature T_R and Inflaton Masses M_ϕ in Non-Thermal Leptogenesis are Calculated Using Table 2, for All Neutrino Mass Models with $\tan^2\theta_{12} = 0.45$

TYPE	(m,n)	$T_R^{min} < T_R \le T_R^{max}$(GeV)	$M_\phi^{min} < M_\phi \le M_\phi^{max}$(GeV)
NH-IA	(6,2)	$6.51x10^6 < T_R \le 8.87x10^6$	$9.99x10^9 < M_\phi \le 5.60x10^{12}$
	(8,4)	$6.01x10^3 < T_R \le 3.94x10^5$	$8.78x10^7 < M_\phi \le 1.40x10^{10}$
NH-IB	(6,2)	$3.7x10^8 < T_R \le 6.15x10^6$	$2.70x10^9 < M_\phi \le 4.79x10^3$
	(8,4)	$1.96x10^{13} < T_R \le 1.49x10^4$	$2.99x10^6 < M_\phi \le 1.52x10^{-3}$
IH-IA	(6,2)	$6.72x10^5 < T_R \le 6.56x10^6$	$6.11x10^9 < M_\phi \le 2.41x10^{11}$
	(8,4)	$5.12x10^5 < T_R \le 3.79x10^5$	$5.31x10^7 < M_\phi \le 7.12x10^6$
IH-IB	(6,2)	$5.04x10^{12} < T_R \le 8.72x10^7$	$1.44x10^9 < M_\phi \le 1.54x10^4$
	(8,4)	$4.68x10^{12} < T_R \le 1.39x10^5$	$7.09x10^7 < M_\phi \le 9.99\,x10^{-4}$

Where $M_p \approx 2.4x10^{18}$ GeV is the reduced Planck mass and g_* is the effective number of relativistic degrees of freedom at reheating temperature. For the reheating temperature the particles involved are all relativistic and for MSSM$g_* =$ 915/4 = 228.75 and for SM $g_* =$ 427/4 =106.75.

Any lepton asymmetry $Y_L \equiv n_L/s$ produced before the electroweak phase transition is partially converted into a baryon asymmetry $Y_B \equiv n_L/s$via sphaleron effects. The resulting Y_B is

$$Y_B = CY_L \tag{20}$$

With the fraction with the fraction Ccomputed to be $C = -8/15$in the MSSM and $C = -28/79$in the SM [62]. The lepton asymmetry, in turn, is generated by the CP- violating out-of-equilibrium decays of the heavy neutrinos

$$N \to lH_u^*, N \to \bar{l}H_u \tag{21}$$

In the framework of non-thermal leptogenesis the lepton asymmetry is given by [62],

$$Y_L = \frac{3}{2}BR(\emptyset \to N_1N_1)\frac{T_R}{M_\emptyset} \in \tag{22}$$

Where $\in$ is the CP asymmetry abd BR is the branching ratio for the decay of the inflaton to the lightest heavy right-handed neutrino. The decay is kinematically allowed provided that

$$M_\emptyset > 2M_1 \tag{23}$$

We will assume that BR ≈ 1, that is the inflaton decays practically only to the lightest of the right-handed neutrinos. This is possible even if the inflaton is heavy enough to decay to all right-handed neutrinos as long as $|\lambda_1|^2 \gg |\lambda_2|^2, |\lambda_3|^2$. Combining the above formulae we obtain

$$Y_B = \frac{n_B}{s} = CY_L = C\frac{3}{2}\frac{T_R}{M_\phi}\epsilon \tag{24}$$

$$\text{Or } T_R = (\frac{2Y_B}{3C\epsilon})M_\phi \tag{25}$$

If we recall that the entropy density for relativistic degrees of freedom is$s = h_{eff}\frac{2\pi^2}{45}T^3$and that the number density for photons is $n_\gamma = \frac{2\zeta(3)}{\pi^2}T^3$, one easilyobtains for today that$s = 7.04n_\gamma$ is related to $Y_B$through the expression,

$$Y_B = n_B/s = 8.7x10^{-11}. \tag{26}$$

The above expression is supplemented by one more boundary conditions: an upper bound for the reheating temperature, $T_R \leq 0.01\, M_1$coming from out-of-thermal equilibrium decay of N_1. Only those models which satisfy simultaneously two additional constraints on $\mathrm{T_R}$ and$\mathrm{M_\phi}$: $T_R^{min} < T_R \leq T_R^{max}$and M_ϕ^{min}<M_ϕ<M_ϕ^{max}, can survive in the non-thermal leptogenesis.

5. CONCLUSIONS

To summarize, we have computed all the contributions to the CP violating asymmetries arising at one–loop in the decays of heavy (s) neutrinos, both in the standard non–supersymmetric Fukugita–Yanagida scenario and in its supersymmetric version. We have discussed the different results present in the literature and showed that the Inflaton mass needed to produce the observe baryon asymmetry 6.5×10^{-10} GeV is found to be 5.60×10^{12} GeV corresponding to the reheating temperature 8.87×10^{6} GeV for the best model. This result is consistent with the Davidson and Ibarra constraints on lepton asymmetry and right-handed Majorana neutrino mass. The baryon number generated in both scenarios was also obtained. A final remark, that leptogenesis in minimal supersymmetric standard model appears slightly better than the non-supersymmetric Fukugita and Yanagita leptogenesis. To confirm this findings this it will be worth investigating the “soft and resonant” leptogenesis.

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